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19-05-2015	Final Report	2-Jan-2013 - 1-Jan-2015

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Final Report: New Forms of Matter in Optical Lattices	W911NF-13-1-0031
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Wolfgang Ketterle	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
Massachusetts Institute of Technology (MIT 77 Massachusetts Ave. NE18-901 Cambridge, MA 02139 -4307	

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U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 63584-PH-DRP.1

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

The project period features multiple advances at different frontiers of ultracold atom science. Our approach has been a joint experimental and theoretical effort. Experimentally, new technologies for optical lattices were implemented, including a two-layer quantum microscope, a flexible hexagonal lattice where the geometry of the lattice can be changed by polarization control, and a new fluorescence detection scheme for potassium using blue light. Experimental studies realized topologically a non-trivial many body system, the Hofstadter butterfly using

15. SUBJECT TERMS

optical lattice, quantum simulator, many body physics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Wolfgang Ketterle
UU	UU	UU	UU		19b. TELEPHONE NUMBER 617-253-6815

Report Title

Final Report: New Forms of Matter in Optical Lattices

ABSTRACT

The project period features multiple advances at different frontiers of ultracold atom science. Our approach has been a joint experimental and theoretical effort. Experimentally, new technologies for optical lattices were implemented, including a two-layer quantum microscope, a flexible hexagonal lattice where the geometry of the lattice can be changed by polarization control, and a new fluorescence detection scheme for potassium using blue light. Experimental studies realized topologically a non-trivial many body system, the Hofstadter butterfly using synthetic magnetic fields, and realized topological excitations in the form of solitonic vortices. Theoretical work provides new directions to explore, including new forms of matter (Chern insulators, quantum phases with SU(N) symmetry, dipolar matter) and new protocols for characterization (entanglement entropy). A new frontier for ultracold atoms is transport experiments for thermoelectric properties with the possibility of new cooling schemes analogous to the Peltier effect. The Hubbard model in optical lattices is providing a system where advanced calculations are verified in experimental studies. New directions are quench experiments and expansion dynamics. These results together show a vibrant field which is even gaining additional momentum.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 165.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

see attached

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	6.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	6.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	6.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	4.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	3.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

see attached

Technology Transfer

none

ARO Final Report

Report Type:	Final Report
Proposal Number:	63584PHDRP
Agreement Number:	W911NF1310031
Proposal Title:	New Forms of Matter in Optical Lattices
Report Period Begin Date:	01/02/2013
Report Period End Date:	07/01/2014

To avoid double listing, the reported accomplishments should not duplicate accomplishments reported in the final report for the DARPA OLE project which ended 5/25/2013. David Weiss was part of another consortium, and his accomplishments are not included in this report.

Organization Information

Massachusetts Institute of Technology
Office of Sponsored Programs
Cambridge, MA 021394307

Authors of report: W. Ketterle

Abstract (**MUST NOT EXCEED THE 200 WORD LIMITATION**). The abstract should include the following components: **specific aims, results of findings and their significance, and plans for the coming year.**

The project period features multiple advances at different frontiers of ultracold atom science. Our approach has been a joint experimental and theoretical effort. Experimentally, new technologies for optical lattices were implemented, including a two-layer quantum microscope, a flexible hexagonal lattice where the geometry of the lattice can be changed by polarization control, and a new fluorescence detection scheme for potassium using blue light. Experimental studies realized topologically a non-trivial many body system, the Hofstadter butterfly using synthetic magnetic fields, and realized topological excitations in the form of solitonic vortices. Theoretical work provides new directions to explore, including new forms of matter (Chern insulators, quantum phases with SU(N) symmetry, dipolar matter) and new protocols for characterization (entanglement entropy). A new frontier for ultracold atoms is transport experiments for thermoelectric properties with the possibility of new cooling schemes analogous to the Peltier effect. The Hubbard model in optical lattices is providing a system where advanced calculations are verified in experimental studies. New directions are quench experiments and expansion dynamics. These results together show a vibrant field which is even gaining additional momentum.

ARO Final Report

(1) Submissions or publications under ARO sponsorship **during this reporting period**. List the title of each and give the total number for each of the following categories:

(a) Papers published in peer-reviewed journals

1. C.J. Kennedy, G.A. Siviloglou, H. Miyake, W.C. Burton, and W. Ketterle:
   Spin-orbit coupling and spin Hall effect for neutral atoms without spin flips.
   Phys. Rev. Lett. 111, 225301 (2013).
2. H. Miyake, G.A. Siviloglou, C.J. Kennedy, W.C. Burton, and W. Ketterle:
   Realizing the Harper Hamiltonian with Laser-Assisted Tunneling in Optical Lattices.
   Phys. Rev. Lett. **111**, 185302 (2013).
3. H. Veksler, S. Fishman, and W. Ketterle:
   A simple model for interactions and corrections to the Gross-Pitaevskii Equation.
   Phys. Rev. A **90**, 023620 (2014).
4. Heavy Solitons in a Fermionic Superfluid, Tarik Yefsah, Ariel T. Sommer, Mark J.H. Ku, Lawrence W. Cheuk, Wenjie Ji, Waseem S. Bakr, and Martin W. Zwierlein,
   Nature 499, 426-430 (2013)
5. Motion of a Solitonic Vortex in the BEC-BCS Crossover
   Mark J.H. Ku, Wenjie Ji, Biswaroop Mukherjee, Elmer Guardado-Sanchez, Lawrence W. Cheuk, Tarik Yefsah, Martin W. Zwierlein
   Phys. Rev. Lett. 113, 065301 (2014)
6. H. Pichler, J. Schachenmayer, A. J. Daley, P. Zoller
   Heating dynamics of bosonic atoms in a noisy optical lattice
   Phys. Rev. A 87, 033606 (2013)
7. H. Pichler, L. Bonnes, A. J. Daley, A. M. Läuchli, and P. Zoller
   Thermal vs. Entanglement Entropy: A Measurement Protocol for Fermionic Atoms with a Quantum Gas Microscope
   New J. Phys. 15, 063003 (2013)
8. J. Schachenmayer, L. Pollet, M. Troyer, and A. J. Daley
   Spontaneous emissions and thermalization of cold bosons in optical lattices
   Phys. Rev. A 89, 011601(R) (2014).
9. Johannes Schachenmayer, Lode Pollet, Matthias Troyer, Andrew J. Daley
   Thermalization of strongly interacting bosons after spontaneous emissions in optical lattices
   Accepted for publication in European Physical Journal Quantum Technology (2014).
   Available at arXiv:1408.1041
10. Observation of chiral currents with ultracold atoms in bosonic ladders
    M. Atala, M. Aidelsburger, M. Lohse, J. T. Barreiro, B. Paredes, I. Bloch
    Nature Physics 10, 588–593 (2014)
11. Probing Real-Space and Time-Resolved Correlation Functions with Many-Body Ramsey Interferometry
    M. Knap, A. Kantian, Th. Giamarchi, I. Bloch, M. Lukin, E. Demler
    Phys. Rev. Lett. 111, 147205 (2013)

12. Direct Measurement of the Zak Phase in Topological Bloch Bands
M. Atala, M. Aidelsburger, J.T. Barreiro, D. Abanin, T. Kitagawa, E. Demler, I. Bloch
Nature Physics 9, 795–800 (2013)

13. Realization of the Hofstadter Hamiltonian with ultracold atoms in optical lattices
M. Aidelsburger, M. Atala, M. Lohse, J. T. Barreiro, B. Paredes and I. Bloch
hys. Rev. Lett. 111, 185301 (2013)

14. A. B. Bardon, S. Beattie, C. Luciuk, W. Cairncross, D. Fine, N. S. Cheng, G. J. A. Edge, E. Taylor, S. Zhang, S. Trotzky, J. H. Thywissen
Transverse Demagnetization Dynamics of a Unitary Fermi Gas
Science 344, 722 (2014)

15. Michael F. Becker, Sih-Ying Wu, and Jinyang Liang, “Encoding Complex Values Using Two DLP® Spatial Light Modulators,” Proc. of SPIE Vol. 8618, pages 86180M-1 to 0M-8, Feb. 2013.

16. Jinyang Liang and Michael F. Becker, “Precise holograms using complex light modulation,” Proc. of SPIE Vol. 8979, pages 89790D-1 to 0D-9, Feb. 2014.

17. Jinyang Liang and Michael F. Becker, “Spatial bandwidth analysis of fast backward Fresnel diffraction for precise computer-generated hologram design,” Applied Optics, vol. 53, no. 27, pp G84-G94, 20 September 2014.

18. J. Schachenmayer, L. Pollet, M. Troyer, and A. J. Daley,
Spontaneous emissions and thermalization of cold bosons in optical lattices,
Phys. Rev. A **89**, 011601(R) (2014).

19. J. Schönmeier-Kromer and L. Pollet,
Ground state phase diagram of the 2d Bose-Hubbard model with anisotropic hopping,
Phys. Rev. A **89**, 023605 (2014).

20. K. Chen, L. Liu, Y. Deng, L. Pollet, and N. V. Prokof’ev,
Universal Conductivity in a Two-Dimensional Superfluid-to-Insulator Quantum Critical System, Phys. Rev. Lett. **112**, 030402 (2014).

21. L. Pollet, N. V. Prokof’ev, and B. V. Svistunov,
Asymptotically Exact Scenario of Strong-Disorder Criticality in One-Dimensional Superfluids,
Phys. Rev. B **89**, 054204 (2014).

22. M. Bukov and L. Pollet,
Mean-Field Theory for Bose-Fermi mixtures,
Phys. Rev. B **89**, 094502 (2014).

23. T. Uehlinger, D. Greif, G. Jotzu, L. Tarruell, T. Esslinger, L. Wang, and M. Troyer,
Double transfer through Dirac points in a tunable honeycomb optical lattice,
Eur. Phys. J. Special Topics, **217**, 121, (2013)

24. Brantut, J.-P.; Grenier, C.; Meineke, J.; Stadler, D.; Krinner, S.; Kollath, C.; Esslinger, T. & Georges, A. (2013), 'A Thermoelectric Heat Engine with Ultracold Atoms', *Science* **342**(6159), 713-715.

25. Georges, A. & Giamarchi, T.C.Salomon; G.Shlyapnikov & Cugliandolo, L. F., ed., (2013), *Many-Body Physics with Ultracold Gases - Les Houches 2010*, Oxford University Press, chapter Strongly correlated bosons and fermions in optical lattices.

26. Grenier, C.; Kollath, C. & Georges, A. (2013), 'Quantum oscillations in ultracold Fermi gases: Realizations with rotating gases or artificial gauge fields', *Phys. Rev. A* **87**, 033603.

27. Poletti, D.; Barmettler, P.; Georges, A. & Kollath, C. (2013), 'Emergence of Glasslike Dynamics for Dissipative and Strongly Interacting Bosons', *Phys. Rev. Lett.* **111**, 195301.

28. Tokuno, A. & Georges, A. (2014), 'Ground states of a Bose-Hubbard ladder in an artificial magnetic field: field-theoretical approach', *New Journal of Physics* **16**(7), 073005.

29. Grenier, C.; Georges, A. & Kollath, C. (2014), `Peltier Cooling of Fermionic Quantum Gases', *Phys. Rev. Lett. 113, 200601*

30. E.L. Hazlett, Y. Zhang, R. W. Stites, K. Gibble, and K. M. O'Hara, "s-Wave Collisional Frequency Shift of a Fermion Clock," *Phys. Rev. Lett.* **110**, 160801 (2013).

31. N.Y. Yao, L.I. Glazman, E.A. Demler, M.D. Lukin, J.D. Sau, "Enhanced Anti-ferromagnetic Exchange between Magnetic Impurities in a Superconducting Host", Phys. Rev. Lett., **113**, 087202 (2014), http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.113.087202

32. Norman Y. Yao, Chris R. Laumann, Sarang Gopalakrishnan, Michael Knap, Markus Mueller, Eugene A. Demler, Mikhail D. Lukin, "Many-Body Localization with Dipoles," Phys. Rev. Lett. **113**, 243002 (2014) http://arxiv.org/abs/1311.7151

33. Michael Knap, Adrian Kantian, Thierry Giamarchi, Immanuel Bloch, Mikhail D. Lukin, and Eugene Demler, "Probing Real-Space and Time-Resolved Correlation Functions with Many-Body Ramsey Interferometry, Phys. Rev. Lett. **111**, 147205, http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.111.147205

34. Tony E Lee, Sarang Gopalakrishnan, Mikhail D Lukin, "Unconventional Magnetism via Optical Pumping of Interacting Spin Systems," Phys. Rev. Lett. **110**, 25, 257204 (2013), http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.257204

35. Mohammad Hafezi, Mikhail D Lukin, Jacob M Taylor, "Non-Equilibrium Fractional Quantum Hall State of Light," New Journal of Physics **15**, 6, 063001 (2013), http://iopscience.iop.org/1367-2630/15/6/063001

36. Norman Y Yao, Alexey V Gorshkov, Chris R Laumann, Andreas M Läuchli, Jun Ye, Mikhail D Lukin, "Realizing Fractional Chern Insulators in Dipolar Spin Systems," Phys. Rev. Lett. **110**, 18, 185302 (2013), http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.110.185302

37. Emanuele G Dalla Torre, Johannes Otterbach, Eugene Demler, Vladan Vuletic, Mikhail D Lukin, "Dissipative Preparation of Spin Squeezed Atomic Ensembles in a Steady State," Phys. Rev. Lett. **110**, 12, 120402 (2013), http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.110.120402

38. Norman Y Yao, Chris R Laumann, Alexey V Gorshkov, Hendrik Weimer, Liang Jiang, J Ignacio Cirac, Peter Zoller, Mikhail D Lukin, "Topologically Protected Quantum State Transfer in a Chiral Spin Liquid, "Nature Communications **4**, 1585 (2013), http://www.nature.com/ncomms/journal/v4/n3/full/ncomms2531.html

39. Emanuele G Dalla Torre, Sebastian Diehl, Mikhail D Lukin, Subir Sachdev, Philipp Strack, "Keldysh Approach for Nonequilibrium Phase Transitions in Quantum Optics: Beyond the Dicke Model in Optical Cavities," Phys. Rev. A **87**, 2, 023831 (2013), http://journals.aps.org/pra/abstract/10.1103/PhysRevA.87.023831

40. N. Yao, C. Laumann, A. Gorshkov, S. Bennett, E. Demler, P. Zoller, M.D Lukin, "Topological Flat Bands from Dipolar Spin Systems", Phys. Rev. Lett., **109**, 266804 (2012), http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.109.266804

41. D. Benjamin, E. Demler, Variational Polaron Method for Bose-Bose Mixtures, Phys. Rev. A 89:033615 (2014)
42. A. Shashi, F. Grusdt, D. Abanin, E. Demler, Radio frequency spectroscopy of polarons in ultracold Bose gases, Phys. Rev. A 89:053617 (2014)
43. F. Grusdt, D. Abanin, E. Demler, Measuring Z2 topological invariants in optical lattices using interferometry, Phys. Rev. A 89:043621 (2014)
44. N. Bernier, E. Dalla Torre, E. Demler, Unstable Avoided Crossing in Coupled Spinor Condensates, Phys. Rev. Lett. 113:065303 (2014)
45. K. Agarwal, E. Dalla Torre, B. Rauer, T. Langen, J. Schmiedmayer, E. Demler, Chiral Prethermalization in supersonically split condensates, Phys. Rev. Lett. 113:190401 (2014)
46. M. Serbyn, M. Knap, S. Gopalakrishnan, Z. Papic, N. Y. Yao, C. R. Laumann, D. A. Abanin, M. D. Lukin, E. Demler, Interferometric probes of many-body localization, Phys. Rev. Lett. 113:147204 (2014)
47. F. Grusdt, A. Shashi, D. Abanin, E. Demler, Bloch oscillations of bosonic lattice polarons, Phys. Rev. A 90:063610 (2014) (Editors' suggestion)

(b) Papers published in non-peer-reviewed journals

None

(c) Presentations
i. Presentations at meetings, but not published in Conference Proceedings

about 165

ii. Non-Peer-Reviewed Conference Proceeding publications (other than abstracts)

1. E.L. Hazlett, Y. Zhang, R. W. Stites, K. Gibble, and K. M. O'Hara, "s-Wave Collisional Frequency Shift of a Fermion Clock," 2013 Joint European Frequency and Time Forum and International Frequency Control Symposium (EFTF/IFC), pp. 1025-1026 (2013)

iii. Peer-Reviewed Conference Proceeding publications (other than abstracts)

1. W. Bakr, L.W. Cheuk, M.J.-H. Ku, J.W. Park, A.T. Sommer, S. Will, C.-H. Wu, T. Yefsah and M.W. Zwierlein
   Strongly interacting Fermi gases
   Proceedings of ICAP 2012 – 23rd International Conference on Atomic Physics
   EPJ Web of Conferences 57, 01002 (2013)

(d) Manuscripts submitted, but not published

1. Emergence of coherence and the dynamics of quantum phase transitions
   S. Braun, M. Friesdorf, S. S. Hodgman, M. Schreiber, J. P. Ronzheimer, A. Riera, M. del Rey, I. Bloch, J. Eisert, and U. Schneider
   ArXiv:1403.7199 (PNAS in press)

2. J. Schachenmayer, L. Pollet, M. Troyer, and A. J. Daley, Thermalization of strongly interacting bosons after spontaneous emissions in optical lattices, arXiv:108.1041 (2014)
3. Kozik, E., Ferrero, M. and Georges, A. (2014) `Non-existence of the Luttinger-Ward functional and misleading convergence of skeleton diagrammatic series for Hubbard-like models' arXiv :1407.5687.
4. Perepelitsky, E. and Shastry, B.S. `Diagrammatic lambda-series for extremely correlated Fermi Liquids' arXiv :1410.5174
5. L. H. Haddad, K. M. O'Hara, and L. D. Carr, "Nonlinear Dirac equation in Bose-Einstein condensates: Preparation and stability of relativistic vortices," submitted to Phys. Rev. A

(e) Books

1. Martin W. Zwierlein
   Superfluidity in Ultracold Atomic Fermi Gases
   review article (200 pages), Chapter 18 in "Novel Superfluids", Eds. K. H. Bennemann and J. B. Ketterson (Oxford University Press, 2014)
2. D. Jervis and J. H. Thywissen
   Making an Ultracold Gas
   Chapter 2 in Quantum Gas Experiments - Exploring Many-Body States, Torma & Sengstock, eds. (Imperial College Press, 2014)

(f) Honor and Awards

Yichao Yu (Ketterle group), 2014 Joel Matthew Orloff award for the most outstanding senior thesis in the MIT physics department

Colin Kennedy (Ketterle group), 2014 Deutsch Award for Excellence in Experimental Physics at MIT

W. Ketterle, 2014 Galileo Ferraris Memorial Lecture Award of the Instituto Nazionale di Ricerca Metrologica, Torino

Lawrence Cheuk (Zwierlein group) wins the MIT Physics Department's Martin Deutsch award for Excellence in Experimental Physics 2013.

Martin Zwierlein promoted to Full Professor (July 2013)

Jennifer Schloss (Zwierlein group) receives Hertz fellowship

Matthew Nichols (Zwierlein group) receives NDSEG fellowship

Markus Greiner, BEC AWARD, BEC CONFERENCE SAN FELIU 2013

Eugene Demler, Siemens Award from Humboldt foundation (Germany)

(g) Title of Patents Disclosed during the reporting period

none

(h) Patents Awarded during the reporting period none

“Technology transfer” (any specific interactions or developments which would constitute technology transfer of the research results). Examples include patents, initiation of a start-up company based on research results, interactions with industry/Army R&D Laboratories or transfer of information which might impact the development of products.

none

Faculty

Wolfgang Ketterle (National Academy Member) (0%)
Martin Zwierlein (4%)
Andrew Daley (25%)
Peter Zoller (National Academy Member) (0%)
Immanuel Bloch (0%)
Joseph Thywissen (0%
Daniel J. Heinzen (5.1%)
Michael F. Becker (3.8%)
Lode Pollet (0%)
Matthias Troyer (0%)
Nikolay Prokofiev (0%)
Boris Svistunov (0%)
Kenneth M. O’Hara, (8 %, 1 month of summer salary)
Markus Greiner (0%)
Mikhail Lukin (0%)
Eugene Demler (0%)

Graduate Students

PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT (Include students who have participated in DARPA research, even if their salary/stipend did not come from the DARPA grant (i.e. their support is zero percent)

Ketterle group
Hiro Miyake (50 %)
Colin Kennedy (50 %)
Edward Su (100 %)
Wujie Huang (50 %)
Junru Li (0%)

Zwierlein group
Ariel Sommer (33%)
Mark Ku (0%)
Lawrence Cheuk (15%)
Cheng-Hsun Wu (33%)
Jee Woo Park (33%)
Melih Okan (0%)
Jennifer Schloss (0%)
Matthew Nichols (0%)
Wenjie Ji (0%)

Biswaroop Mukherjee (0%)

Daley group
Hannes Pichler (0%)
Saubhik Sarkar (100%)

Schneider/Bloch group
Jens Philipp Ronzheimer (0%)
Simon Braun (0%)
Michael Schreiber (0%)
Marcos Atala (0%)
Lucia Duca (0%)
Tracy Li (0%)
Martin Reitter (0%)
Monika Aidelsburger (0%)

Thywissen group
Dylan Jervis, 30%
Graham Edge, 100%

Heinzen/Becker group
Rudy Kohn: 75%
Andy Hutchison: 75%
Niels Bidault (visiting graduate student) 0%

Pollet/Troyer/Prokofiev/Svistunov group
Kun Chen (100%)
Stefan Depenbrock (15%)
Dario Hügel (50%)

O'Hara group
Andrew Marcum (50%)
Arif Mawardi Bin Ismail (40%)
Francisco Fonta (0%)
Yi Zhang (0%)

Greiner group
Florian Huber- 100% MAY, JUNE, JULY, AUG 2013 (4months)
Ruichao Ma- 100% JULY & AUG 2013 (2months)
Philipp Preiss- 100% JULY 2013 (1month), 50% AUG 2013 (1month)
Alexander Lukin 100% JULY 2013 (1month)
Matthew Rispoli 100% JULY & AUG 2013 (2months)
Christie Chiu 100% JULY & AUG 2013 (2months)

Lukin group
Soonwon Choi- 100% AUG & SEPT 2013 (2months); 50% OCT, NOV, DEC (2013) , JAN, FEB (2014) (5months)

Demler group
Kartiek Agarawal (33 %)

Post Doctorates
PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT

Ketterle group
Georgios Siviloglou (100 %)

Zwierlein group
Waseem Bakr (0%)
Sebastian Will (0%)
Tarik Yefsah (0%)
Julian Struck (0%)

Daley group
Johannes Schachenmayer (0%)
Stephan Langer (12%)
Alexandre Tacla (8%)

Schneider/Bloch group
Ulrich Schneider (0%)
Monika Schleier-Smith (0%)
Sean Hodgman (0%)

Greiner group
Sebastian Blatt- 100% AUG 2013 (1month)
Kazi Rajibul Islam- 100% JULY & AUG 2013 (2months)

Lukin group
Steven Bennett 75% APRII, MAY, JUN, JUL. AUG, SEPT, OCT & NOV 2013 (8months)
Jay Sau 25% MAY and JULY 2013 (2months)
Nathalie De Leon 75% MAY, JUNE, JULY, AUG, SEPT, OCT, NOV, DEC 2013 (8months)
Philipp Strack 15% MAY 2103 (1month)
Johannes Otterbach 15% SEPT, OCT, NOV (3months)

Demler group
Vladimir Stojanovich (50 %)
Marton Kanasz-Nagi (50 %)
Richaed Schmidt (50 %)

Master Degrees Awarded
PROVIDE FIRST AND LAST NAME

Zwierlein group
Vinay Ramasesh

Schneider/Bloch group
Josselin Bernardoff
Frederik Goerg

Thywissen group
Ryan Day

Pollet/Troyer/Prokofiev/Svistunov group
Marin Bukov

Georges group
Evgeny KOZIK (postdoc) Nov, Dec 2013
Jernej Mravlje (postdoc) April 2014-June 2014
Edward Perepelitsky (postdoc) April 2014-May 2014

Undergraduate Students

PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT

Ketterle group
Yichao Yu (0%)
Derek Kita (0%)
Yuri Lenskiy (0%)
Sean Burchesky (0%)

Zwierlein group
Vinay Ramasesh (0%)
Elmer Guardado-Sanchez (0%)
Emilio Pace (0%)

Schneider/Bloch group
Pau Gomez Kabelka (0%)
Josselin Bernardoff (0%)
Frederik Goerg (0%)

Pollet/Troyer/Prokofiev/Svistunov group
Janik Kromer (0 %)

Student metric

(All items refer to graduating undergraduates funded by this agreement and the reporting period for this report)

Number of graduating undergraduate students:

6

Number of undergraduate students graduating with degrees in science, mathematics, engineering, and technology fields:
6

Number of graduating undergraduates who will continue to pursue graduate degrees:
6

Number of graduating undergraduates who intend to work for the Defense Department:
None

Number of graduating undergraduates during this period who achieve a 3.5 to 4.0 GPA (Convert GPAs on any other scale to be an equivalent value on a 4.0 scale.):
4

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:
None

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields.
3

Doctorate Degrees Awarded

PROVIDE FIRST AND LAST NAME

Ketterle group
Ed Su

Zwierlein group
Ariel Sommer
Cheng-Hsun Wu

Daley group
Hannes Pichler (University of Innsbruck)

Schneider/Bloch group
Jens Philipp Ronzheimer

Thywissen group
Dylan Jervis

O’Hara group
Yi Zhang

Other staff

PROVIDE FIRST AND LAST NAME, AND PERCENT SUPPORTED BY THE DARPA GRANT

Schneider/Bloch group
Bodo Hecker (0%)
Ildiko Kecskesi (0%)

Georges group
BS Shastry (senior invited researcher) June 2014 (0%)

Scientific Progress and Accomplishments (description should include significant theoretical or experimental advances

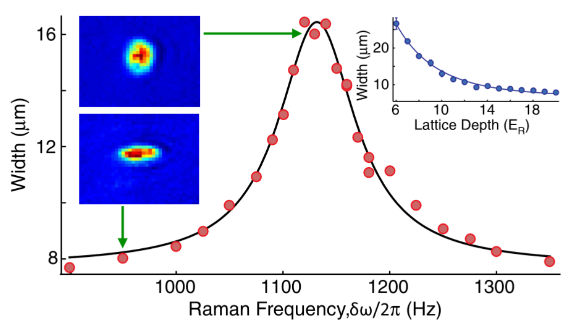
SUMMARY on ONE page for the whole grant period, can include one graphic

Ketterle group

Synthetic magnetic fields for neutral atoms

Systems of charged particles in magnetic fields have led to many discoveries in science -- including both the integer and the fractional quantum Hall effects - and have become important paradigms of quantum many-body physics. Generalizations have led to important developments in condensed matter physics, including topological insulators, fractional Chern insulators, and Majorana fermions. At high magnetic fields, exotic new phenomena like the fractal energy spectrum of Hofstadter's butterfly [1] are predicted to emerge. Its direct observation would require an inaccessibly high magnetic field of one flux quantum per unit cell -- corresponding to approximately 10,000 Tesla in a traditional condensed matter system.

Here we suggest and demonstrate a scheme for synthetic magnetic fields for neutral atoms [2], see also [3]. As a result, neutral atoms have the same Hamiltonian as charged particles in magnetic fields. The trick is that laser beams imprint the same phases into the atomic wave function as vector potentials for electrons. This is done by using laser-assisted tunneling in optical lattices with a potential energy gradient provided by gravity or magnetic field gradients. With this scheme which implements the Harper-Hofstadter Hamiltonian we can simulate magnetic fields of one field quantum per unit cell, which are more than 100 times stronger than available magnets can do for charged particles. This scheme is promising for the realization of the quantum Hall effect and Hofstadter's butterfly.



Observation of laser assisted tunneling in an optical lattices. Shown is the cloud width as a function of Raman detuning after an expansion of 500 ms. Expansion of the cloud occurs only at a resonance condition when the frequency difference between the two Raman beams is equal to the potential energy difference due to the gravitational energy difference between neighboring sties in the lattice. (Inset) Dependence of the laser-assisted tunneling on optical lattice depth. For deeper lattices, the expansion occurs more slowly.

This vector potential is spin-dependent for two spin states with opposite magnetic moments [4]. Atoms in the two states undergo laser assisted tunneling with opposite complex phases. This realizes the spin Hall effect [5], which is a special case of spin-orbit coupling. This spin-orbit coupling scheme is diagonal in the spin basis and does not require near-resonant light for spin flips [6].

1. D.R. Hofstadter, Energy levels and wave functions of Bloch electrons in rational and irrational magnetic fields, Phys. Rev. B 14, 2239 (1976).
2. H. Miyake, G.A. Siviloglou, C.J. Kennedy, W.C. Burton, and W. Ketterle, Realizing the Harper Hamiltonian with Laser-Assisted Tunneling in Optical Lattices, Phys. Rev. Lett. 111, 185302 (2013).
3. M. Aidelsburger, M. Atala, M. Lohse, J. T. Barreiro, B. Paredes, and I. Bloch, Realization of the Hofstadter Hamiltonian with ultracold atoms in optical lattices, Phys. Rev. Lett. 111, 185301 (2013).
4. C.J. Kennedy, G.A. Siviloglou, H. Miyake, W.C. Burton, and W. Ketterle, Spin-orbit coupling and spin Hall effect for neutral atoms without spin flips, Phys. Rev. Lett. 111, 225301 (2013).
5. B.A. Bernevig and S.-C. Zhang, Quantum Spin Hall Effect, Phys. Rev. Lett. 96, 106802 (2006).
6. Y.J. Lin, K. Jimenez-Garcia, and I.B. Spielman, Spin-orbit-coupled Bose-Einstein condensates, Nature 471, 83 (2011).

Zwierlein group

Motion of a Solitonic Vortex in a Fermionic Superfluid

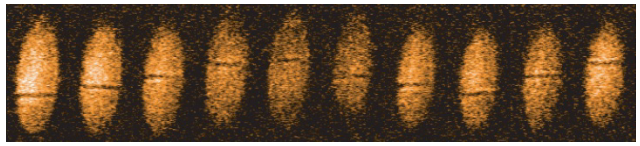


Figure 1 Motion of a Solitonic Vortex in a Fermionic Superfluid. From [2].

Topological excitations are found throughout nature, as defects in proteins and DNA, as dislocations in crystals, or as domain walls in magnets. They affect the transport properties of their host material: The high conductivity of polymers is due to charged solitons, and vortices cause residual resistivity in superconductors. In most systems in nature, the direct propagation of such excitations is not observable directly. Fermionic superfluids of ultracold atoms provide an ideal setting to study the motion of topological defects in real time. In recent experiments at MIT, a topological excitation has been created "on demand" and its free propagation was directly observed [1] (see Figure 1). The inertial mass of this localized object was found to be much larger than the total mass transported with it. In subsequent work [2], the excitation was revealed via tomographic imaging to be a solitonic vortex, a hybrid between a planar soliton and a regular vortex. Such excitations had been predicted to exist in elongated Bose-Einstein condensates, but they had not been experimentally identified before in any superfluid.

For this study, a new kind of tomographic imaging was employed, whereby only a single thin slice of the entire three-dimensional quantum gas could be imaged, thereby revealing the full 3D structure of the topological excitation. This technique allowed the direct observation of the precessional motion of the vortex.

One riddle in the previous study [1] had been the long period of the solitary wave's motion, which meant that the inertial mass of the localized wave must be much larger than the atomic mass that is transported with it, i.e. its gravitational mass. In the present work [2], this long period and the large enhancement of the inertial mass was explained via a superfluid hydrodynamic description of the vortex motion. It turned out that the period was a direct measure of the compressibility to density ratio of the gas, and thus depended strongly on the equation of gas of the system. Tuning the interaction strength of the Fermi gas allowed to vary the equation of state and therefore the compressibility, and with it the vortex period.

The solitonic vortex resembles Josephson vortices causing phase-slips in superconducting tunnel junctions. The experiments have direct implications for understanding transport in other strongly interacting Fermi systems, such as high-temperature superconductors, neutron stars as well as nuclear matter.

1. Tarik Yefsah, Ariel T. Sommer, Mark J.H. Ku, Lawrence W. Cheuk, Wenjie Ji, Waseem S. Bakr, and Martin W. Zwierlein
Heavy Solitons in a Fermionic Superfluid
Nature 499, 426 (2013), doi:10.1038/nature12338

2. M.J.H. Ku, W. Ji, B. Mukherjee, E. Guardado-Sanchez, L.W. Cheuk, T.Yefsah, and M.W. Zwierlein.
Motion of a Solitonic Vortex in the BEC-BCS Crossover.
Phys. Rev. Lett. **113**, 065301 (2014), featured as a Highlight in Physics **7**, 82, 2014

Pittsburgh and Innsbruck groups

During the period of this grant we have made significant process in two key areas related to the engineering of new forms of matter in optical lattices: (1) we have progressed our understanding of heating processes in optical lattices, and how they affect the many-body states produced in these systems; and (2) we have developed a scheme to measure entanglement entropy for spinful fermions in optical lattices.

A key experimental challenge in the realization of complex many-body states in optical lattices is the characterization and control of heating processes. We have continued to study the interplay between many-body dynamics and common heating mechanisms in optical lattices, especially intensity noise on the lattice laser [Phys. Rev. A 87, 033606 (2013)] and spontaneous emissions [Phys. Rev. A 89, 011601(R) (2014)]. One of the aspects that makes this characterization difficult is the role of thermalization in the many-body system. On typical experimental timescales, certain types of excitations cannot be thermalized – the simplest example being atoms that are excited to higher Bloch bands, which cannot thermalize the bandgap energy on short timescales as this energy is much larger than typical energy scales of tunneling and interactions in the lowest band.

For the first time, we have now addressed the question of whether excitations within a Bloch-Band arising from spontaneous emissions can be thermalized [Phys. Rev. A 89, 011601(R) (2014)]. By combining quantum trajectories techniques with time-dependent density matrix renormalization group methods, we were able to compute the relaxation dynamics of bosonic atoms moving in 1D on a lattice after spontaneous emission events. We considered the time-dependence of correlation functions including the quasi-momentum distribution and kinetic energy, and compared these with thermal values from a canonical ensemble (computed via Quantum Monte Carlo methods), in which the temperature is chosen to match the total energy in the system. We found that starting from a ground state for various interaction strengths, we always observed the system relax (or dephase) to a steady-state on a short or moderate timescale. For short-range correlation functions or global quantities such as the kinetic energy, this timescale for relaxation was that is comparable to a few tunneling times, whereas for long-range correlation functions, this timescale is longer. In the superfluid regime, we found that the values to which the kinetic energy and quasimomentum relax are equal to the expected thermal values in a canonical ensemble with the same total energy. However, in the Mott Insulator regime the system relaxes rapidly to a steady-state in which the correlation functions do not take on the value expected from the corresponding canonical ensemble. As a function of interaction strength, the discrepancies in the values begin suddenly at the phase transition point, and become larger for stronger interactions. This behavior can be traced back to the local nature of spontaneous emissions, which localize particles on-site. In this local quench, the resulting dynamics are dictated by the low-energy spectrum of the Hamiltonian, and which particular states are populated by the quench. This leads to significant changes in dynamics at the phase transition point, due to the changes in the low-energy spectrum.

We have also shown how Rényi entropies of order two can be measured for fermionic atoms in optical lattices. This builds on a previous scheme we had presented for spinless bosons, but now makes the measurement of the state purity and entanglement of subsystems accessible for the particularly interesting case of fermionic atoms with spin. Our scheme is based on the ability to produce two copies of the state in an optical lattice system, couple them via tunneling, and them measure the occupation number in a site- and spin-resolved manner. These ingredients are available in quantum gas microscope experiments that are currently under development for fermions. An important aspect to understand in the measurement of these entropies is the interplay between the contribution to the entropy of a subsystem from entanglement and the contribution that comes from the entropy of the complete system at finite temperatures. Both of these are combined into the measured entropy, and to understand these effects and provide a benchmark for experiments, we calculated the entropy of entanglement and total entropy for example cases with interacting Fermions in 1D.

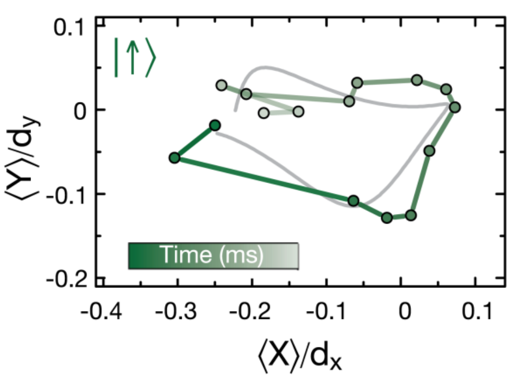
Schneider/Bloch group

During the ‘New Forms of Matter in Optical Lattices’ Program, our team concentrated on two main directions. The first one addressed the question, on how fast new forms of matter can actually form, i.e. how fast long-range or quasi long-range correlations can form? To this end, we experimentally studied the emergence of coherence when crossing the quantum phase transition from a Mott insulator into the superfluid in the Bose-Hubbard model and extracted the coherence length from time-of-flight images. Interestingly, we found non-universal power-laws that indicate that, in realistic situations, the dynamics of these models can go well beyond the critical behavior expected close to the phase transition (S. Braun et al. Arxiv:1403.7199, PNAS in press).

Another main focus was the creation of topologically non-trivial band structures and the observation of the corresponding geometric phases and flow patterns for bosonic atoms in optical lattices. In this context, we could directly measure the Zak phase in 1D topological Bloch Bands created in a bichromatic optical superlattice (M. Atala et al., Nature Physics 9, 795–800 (2013)). The latter results were based on a close collaboration with the group of E. Demler at Harvard University.

Building on this expertise, the team then succeeded in implementing a large homogeneous artificial magnetic field for lattice Bosons in 2D. This system is described by the celebrated Hofstadter Hamiltonian and the team could directly demonstrate the existence of cyclotron orbits in this system (M. Aidelsburger et al. Phys. Rev. Lett. 111, 185301 (2013)).

In a similar system, where the atoms were confined to 1D two-leg ladders, we managed to observe chiral currents (M. Atala et al. Nature Physics 10, 588–593 (2014)), which can be seen as an analogue of the Meissner effect in a classical thin-film superconductor in the presence of a (real) magnetic field.

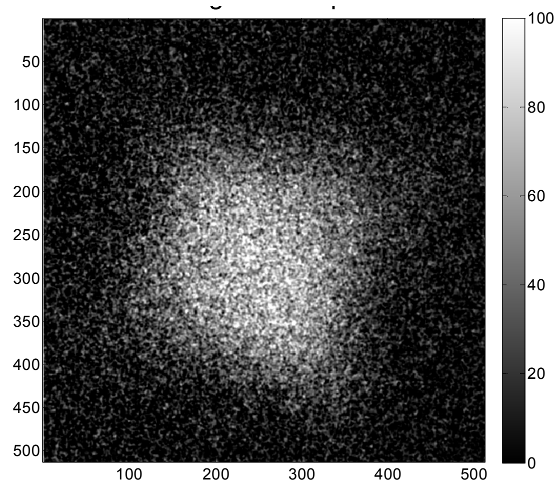


Cyclotron orbit within an individual plaquette in the presence of a large homogenenous artificial magnetic field

Thywissen group

405 nm Fluorescent Images of Lattice Fermions

The Toronto node worked towards high-resolution imaging of fermionic potassium (40K) in an optical lattice. In earlier work, we pioneered laser cooling of 40K using 405 nm excitation to the 5P state. Used for microscopy, this near-violet transition would give an enhancement of resolution, compared to 767 nm excitation to the 4P state. During this grant, we took the first ever fluorescence images using 405 nm light, as shown in the figure below. This is also among the first fluorescent images ever taken of fermions in an optical lattice, at any wavelength.



In-situ image of fermions in an optical lattice. 1.5s exposure at 405 nm, of multiple lattice

Unlike in free space, we found that 405 nm light was not a useful laser-cooling transition in the lattice. Instead, in order to take the image below, atoms were simultaneously cooled using 770 nm excitation to the 4S J=1/2 state. This technique was previously observed to work in free space, but our work confirms that the same transition can also work with strong three-dimensional confinement of a far-detuned optical lattice.

From this image, we estimate that tens of photons were collected on the camera per atom. An increased signal level will be required for site-resolved single-atom imaging. High-resolution imaging and addressing of fermions will enable thermometry, measurements of spatial correlations, and high-resolution manipulation.

Heinzen/Becker group

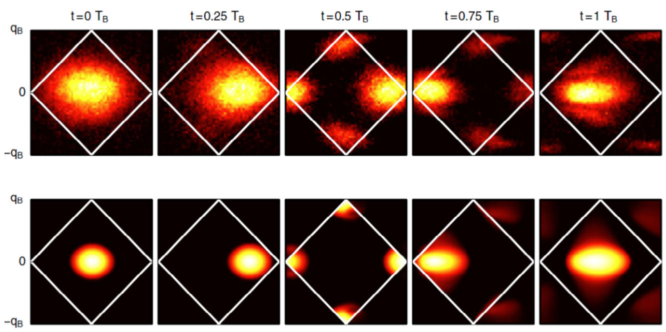
During this period we were working on developing a new imaging technique called complex light modulation (CLM) by a more efficient combination of spatial light modulators. CLM is the ability to control a light-wave's phase and amplitude, thereby allowing complete control of the light-wave at any location. With this ability, it is possible to create improved imaging methods for the consumer, medical, and defense industry as well as applications in holography. The team has successfully created phase-only holograms (POH) and amplitude-only beam-shaping patterns. Also, we have simulated the proposed technique using the combined modulators and published the results. The research apparatus consists of three optical benches, one for testing the amplitude of light, one for testing the phase of light, and one for enabling CLM. Next steps are to combine the phase and amplitude modulation techniques to enable full 3-D holographic image reconstruction.

We completed an apparatus designed to load Bose-condensed atoms into a dipole trap with a shape controlled by the beam shaper. We completed experiments to load laser-cooled atoms into a magneto-optical trap and a magnetic trap. We began experiments to evaporatively cool the atoms into the shaped dipole trap.

Pollet/Troyer/Prokofiev/Svistunov group

The ground state phase diagram of the 2d Bose-Hubbard model with anisotropic hopping was computed by using quantum Monte Carlo simulations, connecting the 1d to the 2d system, see figure. We find that the tip of the lobe lies on a curve controlled by the 1d limit over the full anisotropy range while the universality class is always the same as in the isotropic 2d system. This behavior can be derived analytically from the lowest order renorrmaliztion group equations and has a shape typical for the underlying Kosterlitz-Thouless transition in 1d. Our calculations shed light on recent cold gas experiments monitoring the dynamics of an expanding cloud.

In a joint experiment-theory work on Bloch-Zener oscillations of an ultracold Fermi gas in a tunable honeycomb lattice we compare results from realistic simulations of quantum dynamics of atomic gases with the experimentally observed quasi-momentum distributions. The agreement is excellent. The simulation explains the observed double-peak structure of an interband transferred fraction and absence of the coherent Stückelberg oscillation. In the figure we show time-resolved Bloch oscillations for quasi-momentum distributions with a force pointing along x in the experiment (top) and in the numerical simulation of a 2D trapped system (bottom).



We computed the universal conductivity of the (2+1)-dimensional XY universality class, which is realized at the superfluid-to-Mott insulator quantum phase transition at constant density. Based on large-scale Monte Carlo simulations of the classical (2+1)-dimensional J-current model and the two-dimensional Bose-Hubbard model, we precisely determined the conductivity on the quantum critical plateau, $\sigma(\infty)=0.359(4)$ in units of the conductivity quantum. The universal conductivity is the “hydrogen atom” type problem for developing the physical picture of quantum critical dynamics in the “beyond the quasiparticles” situation. It is also the canonical example of where the AdS/CFT correspondence from string theory can be tested and made to use. For the first time, the shape of our $\sigma(i\omega_n)$ - $\sigma(\infty)$ function in the Matsubara representation was determined with accuracy sufficient for a conclusive comparison with existing theory, and established the particle-like nature of charge transport.

Georges group

Our main activity during this period has been the exploration of a new direction in the field of ultra-cold atomic gases, namely the study of transport phenomena in which the transport of particles and entropy are coupled. These are the analogues of thermoelectric phenomena in the solid-state context. Using theoretical methods based on the Landauer-Buttiker formalism, we predicted that such effects could be observed in a setup such as the one developed at ETH-Zurich, in which particles flow between two reservoirs connected by a constriction with a tunable number of channels and transmission coefficient. The suggested experiment was realized, resulting in a joint publication (Brantut et al., Science (2014)) in which the observation of these effects was reported for the first time. Encouraged by this success, we have recently proposed to use the `Peltier effect in order to achieve cooling of fermionic gases down to lower temperatures than reachable today (Grenier et al. Phys Rev Lett, 2014).

We also pursued during this period the exploration of the dynamics of decoherence in open quantum systems coupled to a dissipative environment. We unraveled intriguing physical effects resulting from the competition of interaction and dissipation. These effects lead to slow dynamics of the decoherence, reminiscent of the dynamics of glassy systems (although in a context without any quenched disorder): Poletti et al., PRL 109, 045302 (2012) and PRL 111, 195301 (2013).

Finally, a last topic investigated during this period deals with more a formal aspect of the many-body problem, with direct relevance to diagrammatic Monte-Carlo methods which have proven so useful in the context of ultra-cold gases. We have shown that these methods, when used to sum-up the so-called `bold' (or skeleton) diagrams can converge to an unphysical solution. We traced this problem to the existence of an unphysical branch of the Luttinger-Ward functional, which turns out not to be single-valued (Kozik et al., arXiv:1407.5687). Investigations of the many-problem using the so-called `Extremely correlated Fermi-liquid' (ECFL) approach were also performed during this period (Perepelitsky and Shastry, 2014).

O'Hara group

A primary goal of the Penn State Fermi gas effort is the observation of anti-ferromagnetic (AF) ordering for a repulsive Hubbard model on a honeycomb lattice. A significant experimental challenge has been the realization of entropies low enough to observe this phase. The approach taken here is to begin with a two-component Fermi gas in a band insulating state of a triangular lattice which can be prepared at extremely low entropy (the entropy in the trapped sample is redistributed to metallic regions which surround the band insulator and which can be subsequently quarantined). The AF phase is then attained by adiabatic state preparation wherein the lattice is continuously transformed from triangular to honeycomb. For adiabatic transformations, the entropy is preserved and the AF phase should be achieved in the honeycomb lattice.

During this reporting period, the Penn State Fermi gas group implemented a dynamically transformable and site resolved triangular/ honeycomb lattice. The lattice is formed from three linearly polarized 532 nm laser beams which intersect at a small angle yielding a relatively large lattice constant (1.25 microns in the honeycomb geometry). This large site spacing allows for single site resolution using off-the-shelf optical components. Direct imaging of the laser interference pattern using the same CCD which images the atoms is shown in the figure to the right. (Note, however, that quantum gas microscopy with this lattice will also require application of an overlapping short-period pinning lattice of sufficient depth to keep atoms trapped in the presence of optical molasses beams.) Instead of using a time-averaged-potential to deform the lattice from triangular to honeycomb (as was described in the statement of work for this grant) the transformation is now instead accomplished by control of the laser polarization. This implementation is demonstrated in the figure to the right which shows triangular, intermediate and honeycomb lattice configurations. This is a preferable technique as the modulation required for the time-averaged potential would likely limit the minimum achievable entropy. For now, the polarization is being controlled with liquid crystal retarders (LCRs). However, fabrication of three independent polarization rotators on a single lithium niobate wafer is currently on-going to replace the LCRs as the LCRs require a 2 kHz modulation of the applied field to prevent ionic buildup. This modulation produces an observable residual modulation of the retardance which may again limit the minimum achievable entropy.

Confinement of a two-component gas of fermionic lithium atoms in a two-dimensional triangular lattice was accomplished during this reporting period. The two-dimensional lattice forms an array of one-dimensional tubes in which the fermions are confined. An additional lattice along the axis of the tubes which will be needed to realize the Hubbard model had not been applied by the end of the reporting period. However, the 1064 nm solid state laser which will be used to form this lattice was made operational during this time. The lithium atoms which were loaded into the 2D triangular lattice were observed to be in the ground vibrational state of the lattice sites as evidenced by the fact that the non-interacting Fermi gas expanded as a ground state Gaussian wavepacket with an initial harmonic oscillator length scale consistent with the site oscillation frequency independently measured by parametric excitation. Prior to application of the final lattice, the 2D array of 1D tubes in the triangular lattice geometry is well suited for studies of the physics of 1D Fermi gases since the tubes are well isolated in the deep triangular lattice potential. In this system, observation of phenomena associated with Luttinger liquids and the defining characteristics of the Fulde-Ferrell-Larkin-Ovchinnikov superfluid phase could be observed. This opens up other possible directions for future research.

Finally, descriptions of prior work supported by DARPA were published in Phys. Rev. Lett. and submitted to Phys. Rev. A. These articles describe our observation of an s-wave collisional frequency shift in a Fermi gas (relevant for optical lattice clocks) and theoretical work studying the creation and stability of relativistic vortices in a condensate confined in a honeycomb lattice.

Greiner group

Atom- and site-resolved experiments with ultracold atoms in optical lattices provide a powerful platform for the simulation of strongly correlated materials. In this grant period we developed a toolbox for the preparation, control, and site-resolved detection of a tunnel-coupled bilayer degenerate quantum gas. Using a collisional blockade, we engineer occupation-dependent interplane transport which enables us to circumvent light-assisted pair loss during imaging and count n = 0 to n = 3 atoms per site. We obtain the first number- and site-resolved images of the Mott insulator “wedding cake” structure and observe the emergence of antiferromagnetic ordering across a magnetic quantum phase transition. We are further able to employ the bilayer system for spin-resolved readout of a mixture of two hyperfine states. This work opens the door to direct detection of entanglement and Kosterlitz-Thouless-type phase dynamics, as well as studies of coupled planar quantum materials.

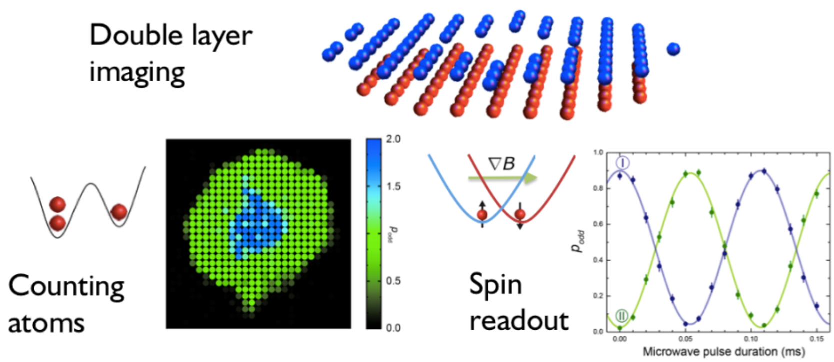


Figure: Imaging double layers enables us to directly measure the atom population on a site, reliably distinguishing between 0,1, 2 and 3 atoms per site. It also allows us to measure spin population with high fidelity.

We also developed a high precision holographic technique that includes accurate aberration correction The idea is to create optical trapping potentials with light waves that are aberration corrected to achieve wave front errors smaller then lambda/50. This becomes possible with a digital mirror device (DMD) spatial light modulator (SLM) used as an amplitude hologram in the Fourier plane of the quantum gas microscope imaging system. The key is to precisely measure aberrations of the optical systems and the entire beam path. This is being accomplished by using the same spatial light modulator to project a sequence of holograms, each creating a pair of beams from two positions in the Fourier plane. Both beams interfere and generate an interference pattern that can be directly measured in situ using the ultracold atoms. This novel system enables us to create arbitrary potential landscapes that are precise and have small structures on the order of 0.5 micrometer.

Lukin group

Systems of strongly interacting dipoles offer an attractive platform to study many-body localized phases, owing to their long coherence times and strong interactions. We explored conditions under which such localized phases persist in the presence of power-law interactions and supplemented our analytic treatment with numerical evidence of localized states in one dimension. We proposed and analyzed several experimental systems that can be used to observe and probe such states, including ultracold polar molecules and solid-state magnetic spin impurities.

Strongly correlated quantum systems can exhibit exotic behavior controlled by topology. We predicted that the $\nu = 1/2$ fractional Chern insulator arises naturally in a two-dimensional array of driven, dipolar interacting spins. As a specific implementation, we analyzed how to prepare and detect synthetic gauge potentials for the rotational excitations of ultracold polar molecules trapped in a deep optical lattice. With the motion of the molecules pinned, under certain conditions, these rotational excitations formed a fractional Chern insulating state. We presented a detailed experimental blueprint for its realization and demonstrated that the implementation is consistent with near-term capabilities. Prospects for the realization of such phases in solid-state dipolar systems were discussed as were their possible applications.

Demler group

We demonstrated that alkaline-earth atoms in optical lattices can be used to implement many-body systems with the SU(N) symmetry group with N as large as 10. We showed that the interplay of the nuclear spin with the electronic degree of freedom provided by a stable optically excited state that enables the study of physics governed by the spin–orbital interaction. Such systems should provide valuable insights into the physics of strongly correlated transition-metal oxides, heavy-fermion materials and spin-liquid phases. Nat. Phys. 6: 289 (2010).

We suggested theoretically and realized experimentally a topological system in 1d using quantum walks of photons. We demonstrated the existence of bound states between systems with different bulk topological properties and verified their robustness to perturbations—a signature of topological protection. We discovered a new phenomenon: a topologically protected pair of bound states unique to periodically driven systems. Nat. Comm. 3:882 (2012).

We proposed theoretically and implemented experimentally a method for studying a Higgs mode in a two-dimensional neutral superfluid close to a quantum phase transition to a Mott insulating phase. We unambiguously identify the mode by observing the expected reduction in frequency of the onset of spectral response when approaching the transition point. Nature 487:454 (2012)

We demonstrated theoretically and then experimentally that 1d condensates after a longitudinal split exhibit prethermalization, where the observables of non-equilibrium, long-time transient states become indistinguishable from those of thermal equilibrium states. Science 337:1318 (2012).

We propose a general method to measure the entanglement entropy. The method is based on a quantum switch (a two-level system) coupled to a composite system consisting of several copies of the original many-body system. The state of the switch controls how different parts of the composite system connect to each other. We showed that, by studying the dynamics of the quantum switch only, the Rényi entanglement entropy of the many-body system can be extracted. We proposed a possible design of the quantum switch, which can be realized in cold atomic systems. Phys. Rev. Lett. 109:020504 (2012) .

We propose d theoretically and implemented experimentally an interferometric method for measuring topological properties of Bloch bands in optical lattices. The key idea was to use a combination of Ramsey interference and Bloch oscillations to measure Zak phases, i.e., Berry's phases for closed trajectories corresponding to reciprocal lattice vectors. Nature Physics 9, 795 (2013).